

# Human Cargo Resupply Logistics at Mars Using 150kW SEP Tug Cyclers

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**Abstract**—The ultimate goal of the Evolvable Mars Campaign is to build up a sustainable outpost at Mars that would be continually staffed with rotating crews. During this stage of human Mars exploration, it would be necessary to provision the crews with equipment and supplies both before and during their missions. In this paper, we study the use of 150 kW reusable SEP tugs as a means to deliver elements both to orbit and to the surface. The SEP tugs would make use of technology currently being developed for the proposed Asteroid Robotic Redirect Mission (ARRM). They would also be used to deliver food and supplies to sustain the crews similar to resupply missions for the International Space Station.

The SEP tugs envisioned would be staged at a quasi-stable Lunar Near Rectilinear Orbit (NRO). The tugs would then mate with cargo vessels and xenon propellant being delivered by an SLS launch vehicle and continue on to Mars orbit where the cargo is delivered and the SEP tug returns to NRO to repeat the process. It was found that it is more efficient to deliver surface cargo via direct launch and entry versus using the tug cycler.

Thousands of optimized low-thrust trajectories were simulated in order to create “Bacon plots” (like porkchop plots, but for low thrust transfers) in order to map out potential trajectories for dates from 2039 to 2052. This study maps out the buildup of a surface outpost as well as the necessary orbital and surface resupply launches in order to maintain it. In the steady state, a cadence of 9 cargo launches is required every 4 years to sustain the human outpost.

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## 1. INTRODUCTION

The culmination of NASA’s Journey to Mars through its Evolvable Mars Campaign (EMC) is a sustainable

infrastructure at Mars that will be used by multiple human crews. In 2015, Price, et al. presented a stepwise approach towards landing humans on Mars [1][2]. The pathway put forth was similar to others in that it made use of the capabilities of the Space Launch System (SLS) to slowly build up the human presence at Mars in a sustainable and affordable manner. This “minimal architecture” approach begins with a crewed mission to Phobos in the mid-2030’s, progresses towards short-stay missions on Mars, and then culminates with regular long-stay missions at a permanent outpost in the 2040’s.

Regardless of the mission architecture and its requisite pieces, human spaceflight missions by definition become sustainable by a resilient supply chain cadence that provides for ample reduction of risk to mission and crew. The authors herein introduce early study results which support a hypothesis that such a supply chain is indeed achievable within the timeline outlined in the NASA EMC. The current investments in the SLS and Solar-Electric Propulsion (SEP) powered spacecraft, along with derived logistics carrier concepts taken from existing cargo spacecraft, form the foundation of the architecture analyzed.

With an eye toward utilization of these assets, the authors investigated various mission designs in support of both landed cargo, as well as orbital cargo such as return supplies and other consumables. The results presented reveal a compelling case for the ability of current spacecraft investments to meet the needs of a Martian supply chain that the human spaceflight community can entertain utilizing in future considerations of human missions to Mars.

## 2. STUDY METHODS AND ASSUMPTIONS

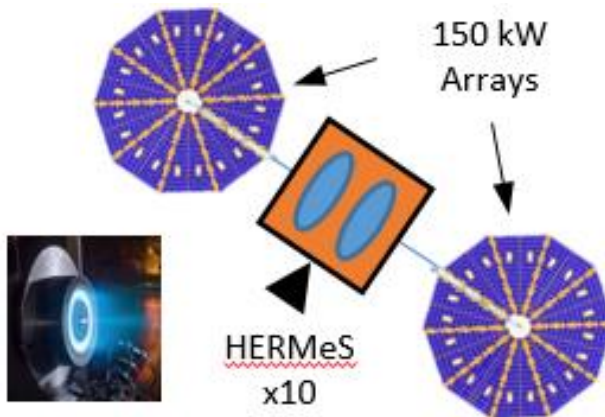
In order to make the problem of designing an architecture to meet the logistical needs of a sustained human outpost on Mars more tractable, it is necessary to make a number of simplifying assumptions. None of the mission elements presented here are intended to be detailed designs, but rather serve as suitable placeholders that would allow for broad architecture design from which insights may be drawn.

## SEP Tugs

Our notional SEP tug utilizes up to 10 HERMeS Hall-effect thrusters [3] and has refillable xenon propellant tanks. It is a high-heritage follow-on to the Asteroid Robotic Redirect Mission (ARRM) which is developing a 50 kW SEP spacecraft propelled by 4 HERMeS engines. Our SEP tug would be powered by 150 kW (1 AU) arrays and is roughly three times the size of the ARRM spacecraft, making use of many similar components. (see Figure 1). It is capable of docking/undocking to support multiple round-trips. The dry mass of the SEP tug is approximately 8 mt. (This is consistent with other studies). A constant 10 kW is diverted for spacecraft systems and margin, leaving 140 kW for the propulsion system. Each HERMeS engine provides 585 mN of thrust and 2660 seconds of Isp when receiving its maximum power of 14 kW. At Earth there is enough power to run all 10 engines, diminishing to 3-4 engines at Mars as available solar power is reduced. Assumptions for the SEP tug are summarized in Table 1.

**Table 1 - Assumed Values for Notional SEP Tug**

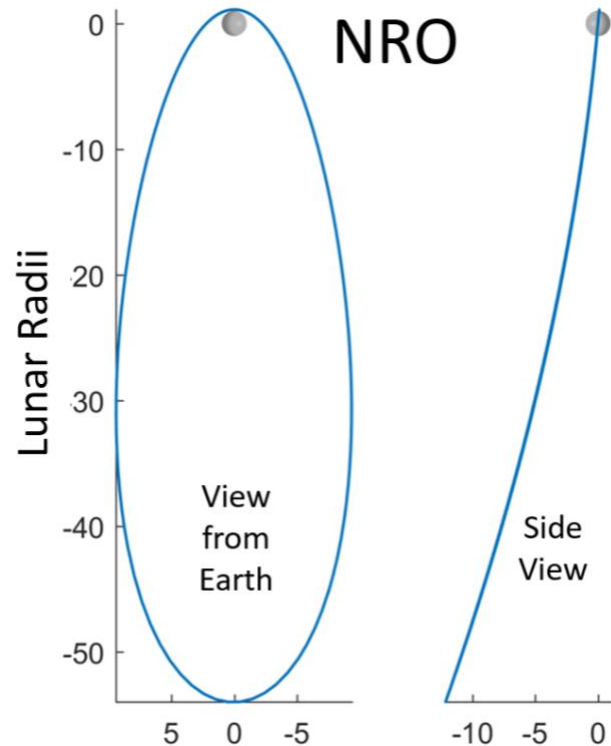
Parameter	Value	Units
Dry Mass	8	mt
Power (1 AU)	150	kW
Thruster	HERMeS	(x10)
Specific Impulse (Isp)	2660	seconds
Thrust	585 (each)	mN
Max Xenon	16	mt



**Figure 1 - The notional SEP tug would use up to 10 HERMeS (inset) engines and 150 kW of power. Nominally it would weight 8 mt dry and have large, refillable xenon tanks.**

Notionally, the SEP tug is delivered to a lunar Near Rectilinear Orbit (NRO) [4], where all mission staging occurs. The basic properties of the NRO are a low perilune near one of the poles (90° inclination), high apolune, a period of around 9 days, and an orbital plane facing Earth as in Figure 2. This type of orbit balances the competing needs of a staging orbit, providing easier access to the lunar surface

than a Distant Retrograde Orbit, and easier access to deep space than a Low-Lunar Orbit [5][6]. Because the orbits are unstable (requiring ~10 m/s per year for stationkeeping), the tug departs the NRO and vicinity of the Moon with minimal  $\Delta V$ . A combination of solar perturbations and SEP thrusting increases the energy with respect to the Moon, so that a lunar gravity assist can cause the tug to escape Earth with a  $C_3$  of around 2 km<sup>2</sup>/s<sup>2</sup>. This energy raising process takes approximately 4 months and 100 m/s of  $\Delta V$ . At the end of the resupply mission this process is reversed to capture back into the NRO.

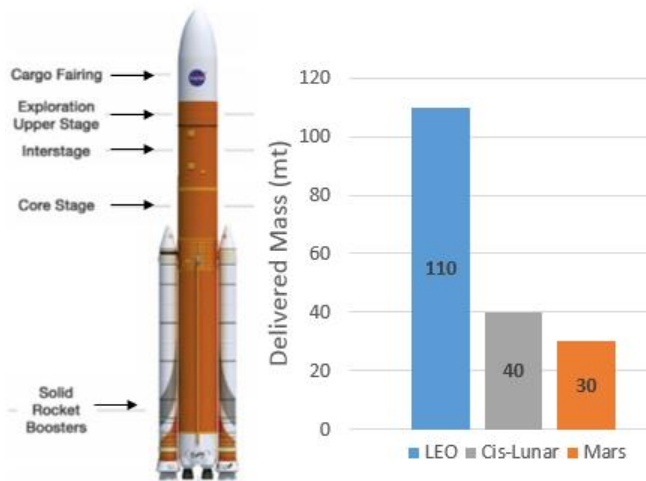


**Figure 2 - Example Near Rectilinear Orbit (NRO) about the Moon. It is an elongated polar orbit that remains "face on" to the Earth. A minimal amount of energy is need to arrive/depart NRO from heliocentric space. This example has a perilune of 200 km and a period of 8.3 days.**

## Launch Vehicle

The NASA Space Launch System (SLS) is the agency's selected launch vehicle for exploration class crewed missions as well as potential deep space science missions. In its early launch configuration, scheduled for a 2018 launch, the SLS consists of a core stage using four RS-25 main engines, 2 five-segment solid rocket boosters, and a derivative of the Delta IV Heavy second stage known in the SLS program as an interim cryogenic propulsion stage (iCPS). The SLS configuration launching in 2018 is known as the 'Block 1' vehicle [7]. The Block 1 SLS is capable of sending approximately 25 mt to a trans-lunar injection (TLI). The

SLS, along with other NASA human spaceflight hardware programs, is an evolvable vehicle; it is anticipated that it will quickly evolve to a Block 1b configuration (Figure 3) that would use a larger upper stage known as the Exploration Upper Stage (EUS). The Block 1b configuration is anticipated to deliver 40 mt to TLI; deriving from the typical lunar C3 value, the payload to a Trans-Mars Injection (TMI) likely would be ~30 mt.



**Figure 3. SLS Block 1b Assumed Capabilities**

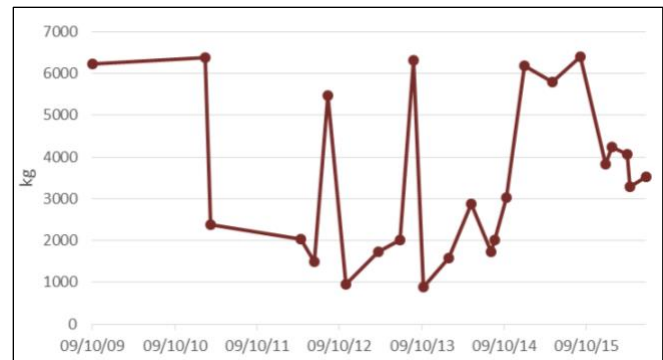
### Logistics Requirements

Variations in logistics requirements across mission types must be assessed in terms of both experience and expectations. Investigating delivered mass in support of ISS missions led the authors to assess the mission duration from launch of assets to delivery at ISS. Because of the short duration of the logistics timeline, items such as fresh fruit and other nominally perishable items were considered acceptable. Also, nitrogen and oxygen tanks are part of the ISS consumable masses delivered due to the nature of the Environmental Control and Life Support System (ECLSS), giving the ISS mission a higher mass logistics requirement than might otherwise be considered for a human spaceflight mission.

As the length of the logistic supply chain increases, the nature of the cargo needs to be considered as well. Considerations include micro-systems, regenerative ECLSS (e.g. higher percentage of loop closure than current LEO-based systems), and storability for longer durations of consumables for longer duration supply chains.

Between September 2009 and May 2016, non-Russian delivered payload to the ISS was over 84.5 mt (see Figure 4). This conservative assumption sets an annual rate of ~13 mt of cargo to support a crew of six at ISS. As human space exploration ventures beyond LEO, both the efficiency of cargo and the efficiency of delivery method need to improve for a resilient supply chain execution. For the anticipated

logistics for future human Mars missions, we used the conservative ISS non-Russian delivered mass assumptions and came to a value of ~5.9 kg per mission day per crew member as a heuristic to investigate the exploration mission requirements to support logistics for a crewed mission.



**Figure 4 - ISS Non-Russian Delivered Payload: September 2009 - May 2016.**

Using this assumption, a crew of 4 on a mission to Mars would require, after arrival at Mars assuming all logistics for the transit to Mars were brought along for the transit journey, 4.3 mt of logistic supply every six months after arrival at Mars. We began with this assumption and designed a Mars logistics supply campaign for both orbital and landed mass requirements.

### Mission Elements

Crewed missions to Mars require many elements no matter what architecture is employed. A sustained outpost on Mars would need many launches to send the infrastructure needed to assist the crew throughout their journey. They will need habitats, propulsion modules, landers, ascent vehicles, etc. There are virtually an unlimited number of ways to orchestrate the mission architecture in terms of types of mission elements, staging locations, and mission sequences. For the purposes of this study we use element masses and an architecture somewhat similar to [1], [2], and [8]. The specifics and feasibilities of the infrastructural elements are not crucial to the purpose of showing a robust method of cargo delivery and resupply.

Table 2 lists the mission elements used along with rough masses. For elements that are not part of the cargo supply chain, such as the Mars Ascent Vehicle (MAV) or surface habitat, the mass allocation is somewhat inconsequential to the resupply architecture. The in-space propulsive elements (TEI, MOI, and Mars Orbit booster) would be delivered and prepositioned by the SEP tug and therefore need to have an assumed mass. Each of these elements weigh 25-30 mt, which is near the limit of what the tug could deliver to High Mars Orbit (HMO – 5-sol for this study) under our assumptions. One of the great benefits of low-thrust missions is the ability to be flexible to change. When masses increase (or decrease) the trajectory can (and often must) be modified to accommodate the change and meet the new requirements.

**Table 2 - Representative Mission Elements and Mass Allocations**

Mission Element	Mass Allocation	Includes Prop?
<i>Crew</i>		
Orion (Command + Service)	20 mt	yes
Deep-Space Habitat (DSH)	30 mt	no
Surface Habitat (HAB)	35 mt	no
<i>Propulsive</i>		
TEI Stage	26 mt	yes
MOI Stage	28 mt	yes
LMO-to-HMO Booster Stage	26 mt	yes
Crew Lander/MAV	50 mt	yes
Exploration Upper Stage (EUS)	14 mt	no
SEP Tug	8 mt	no
<i>Resupply</i>		
Orbital Resupply Module	15-30 mt	no
Surface Resupply Module	20-30 mt	yes

The orbital resupply module is a flexible cargo vessel that has an assumed dry mass of 8 mt. It is capable of carrying 7 to 22 mt of crew consumables (food, water, supplies) as well as other liquids and gases. Its purpose is to mate in HMO with the deep space habitat (DSH) and resupply it for the journey home. It could also serve as a resupply depot for other elements.

Delivering cargo to the surface requires more supporting mass to achieve entry, descent, and landing (EDL). A gear ratio of 3-to-1 was assumed for entry to useful landed mass. For a lander of 30 mt at entry, roughly 10 mt are allocated to the aeroshell and entry systems, 10 mt to the terminal landing and structure, and 10 mt to useful cargo for the crew.

### 3. TRAJECTORY ANALYSIS – BACON PLOTS

In order to characterize mission design parameters (dates, masses, and durations) for the cargo missions, thousands of optimized trajectories were generated. By exploring a wide range of parametric combinations we are able to create a better map of the trade space we seek to explore. This allows us to see the “lay of the land” in order to evaluate where our desired missions are feasible, and to know whether any “peaks, valleys, plateaus, or cliffs” may lay in the vicinity. Plotting performance parameter contours versus launch and arrival dates creates the SEP analog to a ballistic Porkchop plot, which is called a “Bacon Plot” [9].

Low-thrust mission design analysis was carried out using MALTO, a fast, medium-fidelity low-thrust optimizer developed at JPL.[10]. MALTO stands for Mission Analysis Low Thrust Optimizer. This tool generally exhibits robust convergence and can be run in parametric mode with fast, accurate results. We used MATLO to generate thousands of trajectories by sweeping through all launch/arrival date pairs

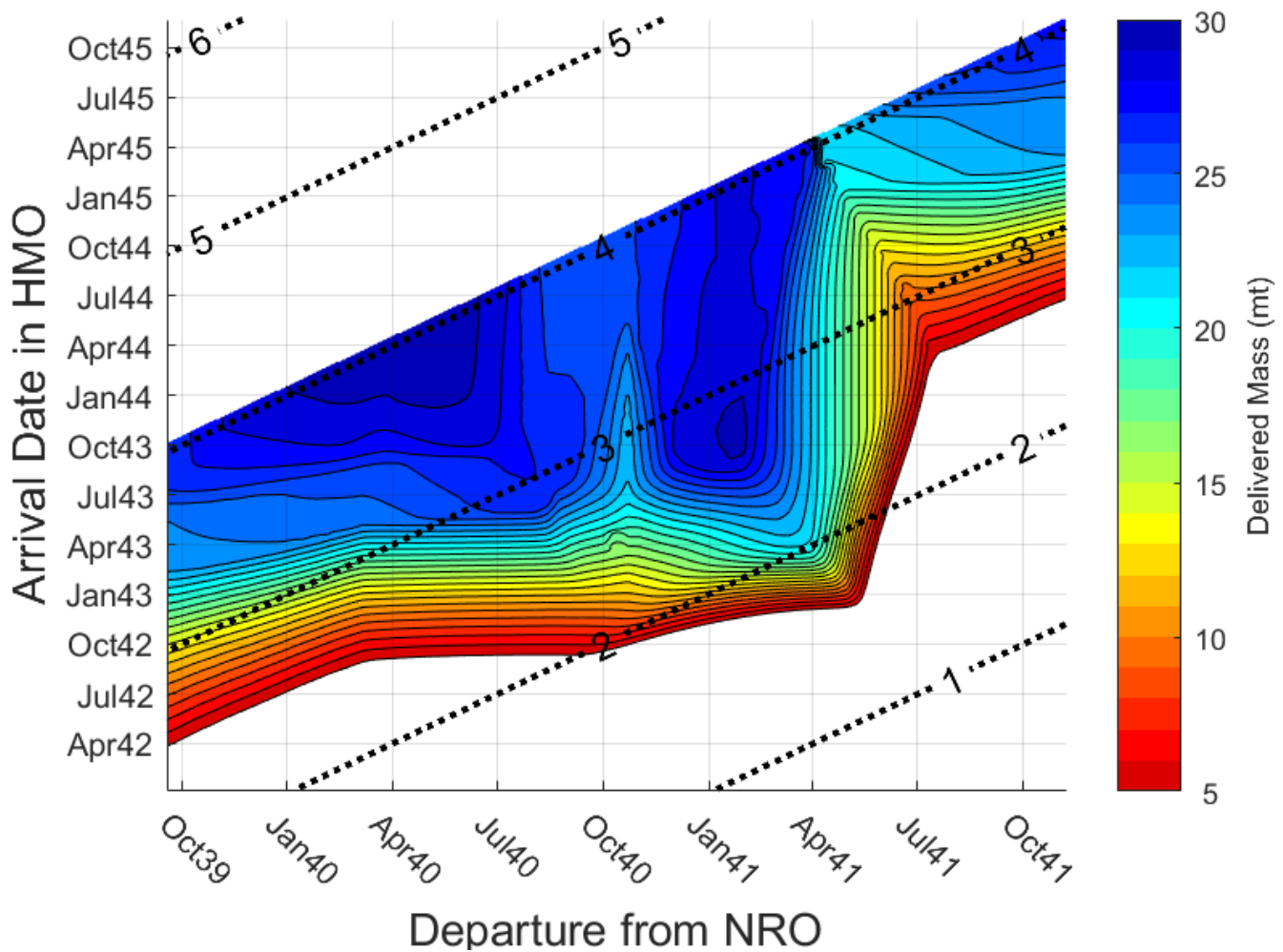
for 2038-2054. This covers a complete set of the 15-year (7 opportunity) Earth-Mars cycle. For dates outside this range the results can just be “shifted” from the representative results 15 years away. However, it was found that low-thrust trajectories do not vary as significantly from opportunity to opportunity as do ballistic transfers.

For Earth-to-Mars trajectories the simulations begin with the SEP tug in NRO mated with the mission element (cargo module or propulsive element) to be delivered to Mars orbit along with the requisite xenon propellant. This gives a maximum starting mass of 48 mt – 8 mt for the SEP tug dry mass and 40 mt from the maximum throw mass of the SLS 1b to a C3 of -2 km<sup>2</sup>/s<sup>2</sup> (NRO). The transfer begins with 4 months and a nominal  $\Delta V$  to affect a series of gravity assist maneuvers and depart towards Mars with a C3 of +2 km<sup>2</sup>/s<sup>2</sup>. From this point the MALTO software finds the optimal thrust profile to minimize propellant usage over the range of dates to arrive at Mars and begin the short spiral down to a 5-sol elliptical staging orbit (HMO). The spiral would roughly require 750 m/s and 90 days. But with some assistance from the ACS thrusters this can be reduced to 250 m/s and 30 days.

Figure 5 shows contours of the maximum mass that can be delivered to HMO by the SEP tug in the 2041 opportunity. (Similar bacon plots can be shown for the other opportunities). Since this plot shows deliverable cargo, it does not include in the mass values shown the 8 mt for the SEP tug and the 2 mt for the xenon needed for the tug to return to NRO. We also allocate mass for 6% propellant margin on all xenon. The resulting mass is what can be delivered to HMO. In the case of cargo delivery, some fraction of it must be allocated for the mass of the container vessel and docking mechanisms.

One of the key features of the SEP bacon plot is that a feasible trajectory exists for any launch date. However, the effects of the planetary synodic period are still present. There are only certain times where fast transfers (~2 years) are possible. These dates roughly correlate with the natural ballistic opportunities. The other feature to note is the nearly constant arrival date for a given mass over a very long span of launch dates. If you follow the light blue contour (20 mt) in Figure 5 you will notice that the arrival date at Mars is around February of 2043 for launches from late 2039 until April of 2041. At that point the Mars arrival date jumps to mid-2045 and the pattern repeats. Also note that the cutoff of data longer than 4 years of transfer time is simply due to the limits of the parameters explored. Feasible trajectories exist for all durations longer than this, presumably with delivered masses in the “deep blue” range of near 30 mt as SEP transfers tend to get more efficient as time-of-flight increases. There is a natural asymptote as the transfer  $\Delta V$  approaches that of a Hohmann transfer (which in this cases is very close to 30 mt).

The process is reversed for the return trajectory of the SEP tug. In this case the mass delivered to NRO is fixed at the dry mass of the SEP tug – 8 mt. MALTO then seeks to find the minimum propellant mass for the return trip. The large



**Figure 5 - Bacon Plot for Earth-to-Mars transfers around 2041.** Colored contours show the maximum delivered cargo mass to HMO for any date pair over one synodic period. The diagonal dashed lines show constant transfers times in years. This includes 3 months to leave NRO and 1 month to spiral down to HMO.

solar arrays and powerful engines lead to faster natural trip times for the lighter vehicle. The Mars-to-Earth Bacon plot in Figure 6 shows contours of required propellant mass instead of maximum delivered mass. We can see the similar pattern of a near constant arrival date for a given mass over a long period, followed by an abrupt jump to an arrival 26 months later. Note that most transfers can be covered by 2000 kg of xenon (light blue and darker). For transfers that begin before July of 2043 the tug will arrive around October of 2044. After that date the arrival date at NRO jumps to late 2046. There is a period of about 9 months out of every 26 where a return transfer of less than 2 years is possible.

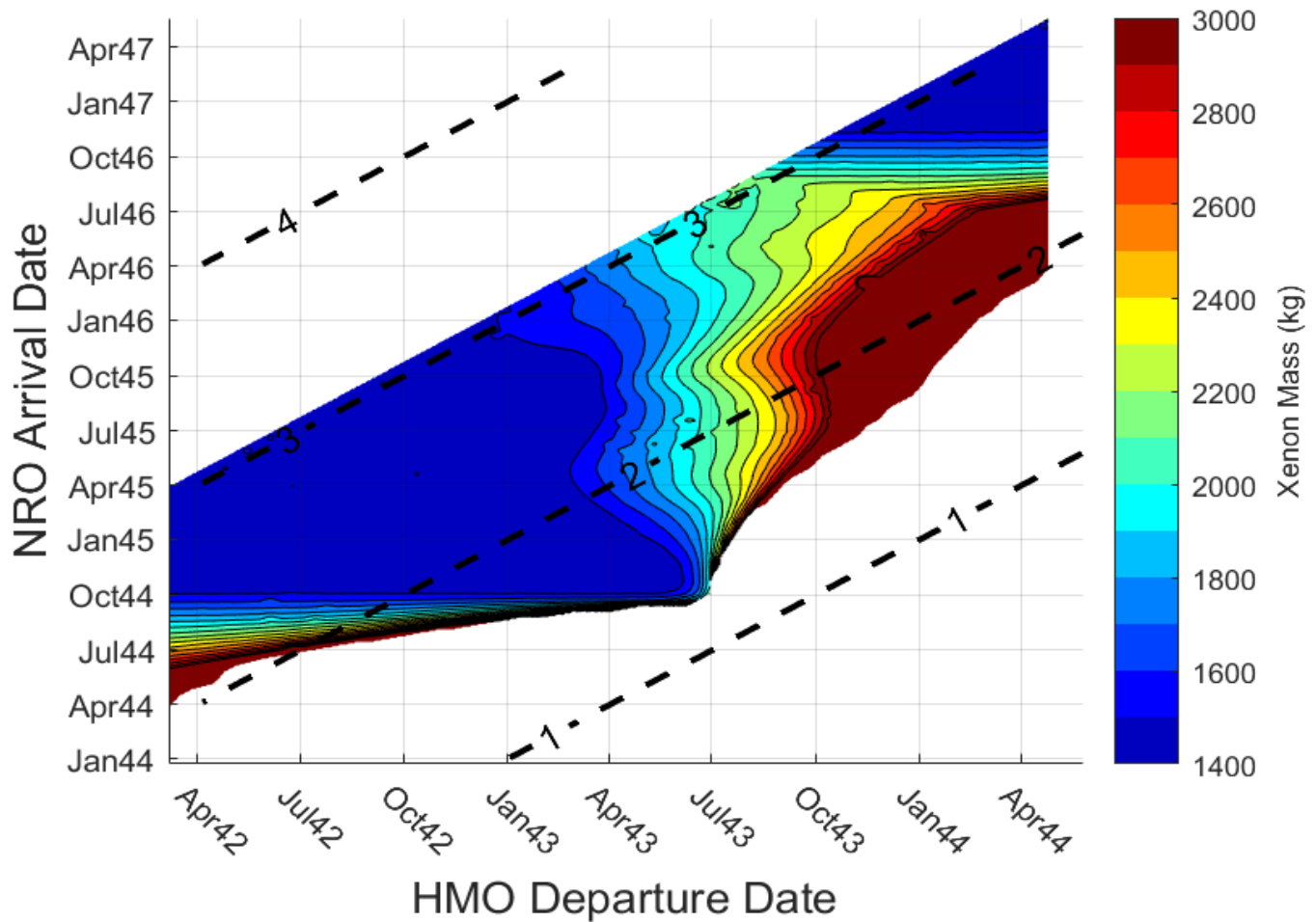
For other opportunities the Bacon plots look quite similar, with the same stair-step feature of constant arrival dates. The contour shapes vary slightly and the masses are typically within  $\pm 5\%$ . It is much more difficult to declare one opportunity “better” than another as it is for ballistic transfers. In fact, shifting the plots by a multiple of 780 days is often sufficient for an initial estimate for another opportunity.

#### 4. RESUPPLY ARCHITECTURE

The primary purpose of this study was to identify the logistical needs of a future human outpost on Mars and analyze mechanisms to deliver the needed cargo in an efficient manner, subject to a set of basic assumptions laid out in Section 2. It is common in the evaluation of most human mission architecture concepts to estimate a total required initial mass in Low Earth Orbit (IMLEO) by aggregating the required mission elements and their propellant. The number of launches is then calculated by dividing the IMLEO by the proposed lift capability of a heavy-lift launch vehicle. Sometimes more specifics are given about the launch order and manifests, but rarely are specific trajectories and launch frequency feasibility included in much detail.

This study addresses the ability to launch the requisite architectural elements with cargo launches adequately interspersed. The SLS launch vehicle is quite large and would be difficult to launch too frequently in any financial





**Figure 6 - Mars-to-Earth Bacon Plot for 2043.** Colored contours show the xenon mass required to deliver the 8 mt SEP tug from HMO to NRO. The diagonal dashed lines show constant transfers times in years. This includes 1 month to spiral up from HMO and 4 months to achieve NRO.

environment. The greater the separation between launches the easier it would be to sustain a Martian outpost. However, ballistic interplanetary transfers have a steep optimum where performance falls off quickly if not timed right. Launching more than 2-3 times per opportunity would be quite difficult if constrained to the few months of optimal planetary alignment. One way to address this problem is by launching space storable mission elements many months earlier to a High Earth Orbit (HEO). They wait there for a future launch where additional mass and the cryogenic EUS is mated and performs TMI – thus doubling mass sent on an optimal trajectory.

Another way to address the problem of a crowded launch season is the ability of SEP missions to depart on any date. Cargo and other un-crewed elements are free to launch outside of the ballistic season as well as take longer to arrive at Mars. This added time also augments the capability of the launch vehicle performance by 25-50%. These are primary reasons that SEP tugs are used in the proposed logistics architecture for a sustainable outpost at Mars.

The proposed SEP tugs can be used to either deliver cargo to Mars orbit or directly to the surface. A typical mission sequence for each are as follows:

**Orbital resupply missions** (Figure 8**Error! Reference source not found.**a) - an SLS launch vehicle, capable of lifting about 40 mt to NRO, sends a cargo vessel to rendezvous with the SEP tug. The mission propellant for the round trip is transferred to the tug and the spacecraft begins its trajectory by performing a lunar gravity assist to send it towards Mars. The SEP engines then bring the cargo to Mars and spiral down to the 5-sol elliptical staging orbit. The detached SEP tug then begins its journey back to lunar NRO.

The maximum mass that can be delivered to HMO is around 30 mt, as shown by the bacon plot in **Error! Reference source not found.** Table 3 shows an example timeline for an orbital resupply round trip that makes use of the faster trajectories in the bacon plot and completes the journey in just under 4 years, delivering 26 mt. Under less favorable dates, the round trip would likely take closer to 6 years.

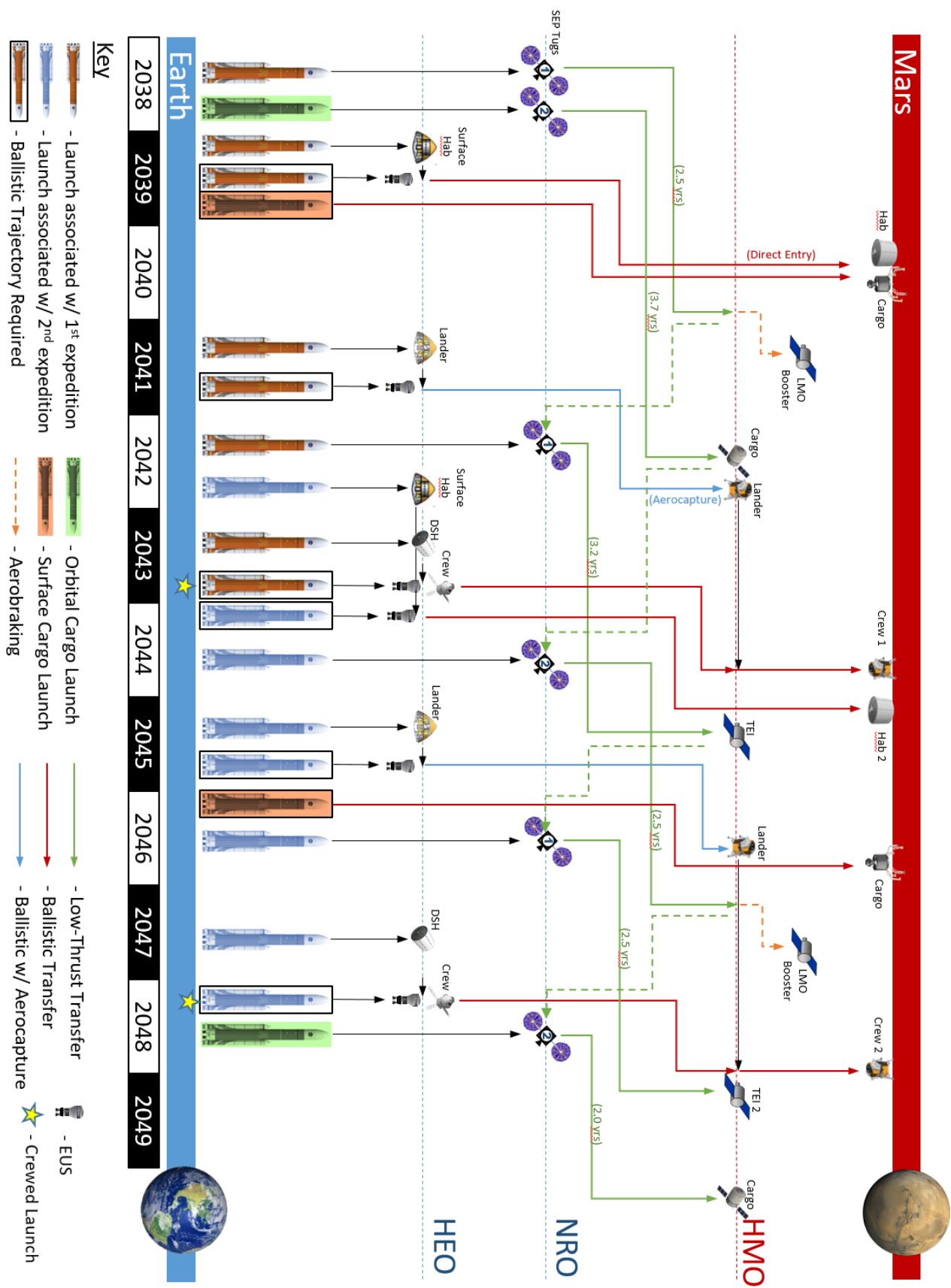


Figure 7 - Representative architecture sequence for the first 2 crewed expeditions to Mars. SEP tugs are used to deliver elements and logistics to high Mars orbit (HMO) and cycle back to a Near-rectilinear orbit (NRO) at the Moon. Surface cargo is delivered via ballistic trajectory and direct entry. Launches are separated by at least 3 months, which is facilitated by the flexible nature of SEP trajectories.

**Table 3 - Example Timeline for fast orbital resupply mission. This sequence delivers 26 mt in 47 months under ideal circumstances. Typical high-mass deliveries would require ~6 years before the tug was ready for the next mission.**

Event	Date	Elapsed Months
Launch	Mar-43	0
Depart NRO	Apr-43	1
Heliocentric Transfer	Jul-43	4
Mars Sphere-of-Influence	Jun-45	27
Arrive at HMO	Jul-45	28
Depart HMO	Aug-45	29
Lunar Fly-by	Nov-46	44
Final NRO	Feb-47	47

**Surface resupply missions** (Figure 8b) - the SEP tug scenario would follow the same model as previously described, except that it would not enter Mars orbit. Instead, it would fly by hyperbolically and drop a landing element with an entry velocity of less than 6.5 km/s. The tug would then continue onward back to NRO. When optimized, this results in a significant (>35 mt) delivery mass to entry. These missions require 30-40% less xenon than orbital mission due to the fact that they do not need to descend and ascend from the Mars gravity well.

Surface cargo drop-off missions typically take 3 to 3.5 years to complete the round trip, with roughly 2/3 of that being the outbound leg. Maximum drop off mass is only achieved near the optimal alignment dates each opportunity. This does not cause problems with launch frequency, however, since they can loiter in NRO post-launch for an indefinite amount of time awaiting a favorable alignment.

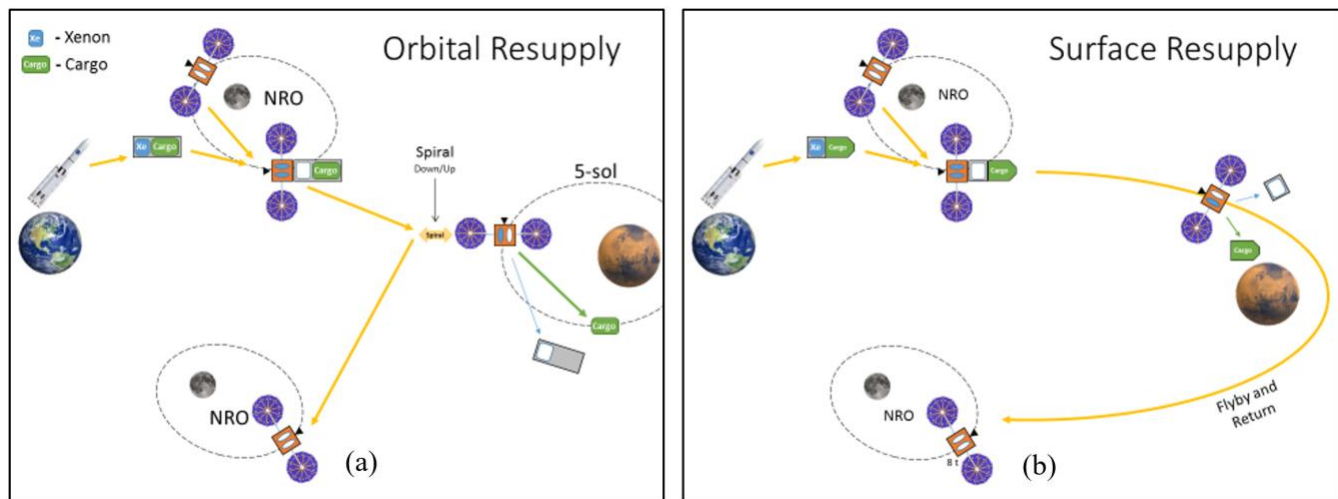
Of course, cargo missions can be launched directly to Mars without the use of a SEP tug. The SLS, after all, is capable of throwing ~30 mt to a C3 of 10 km<sup>2</sup>/s<sup>2</sup>. For orbital missions a chemical MOI of roughly 800 m/s would be needed, which reduces the delivered mass to < 22 mt. Since most elements going to HMO are larger than this, in addition to launch frequency issues around ballistic minima, it was decided that a SEP tug was enabling.

For surface resupply, however, a direct SLS launch and entry was found to deliver sufficient mass in most scenarios and eliminates the complexity of the SEP tug architecture for surface resupply. Direct entry eliminates the need to perform any large in-space maneuvers and takes advantage of the Martian atmosphere. The complexity and cost of using a SEP tug and rendezvous is not warranted for a mere 10-15% increase in entry mass. For this reason we do not use the architecture shown in Figure 8b.

An example sequence of launches was devised that builds up and supports a sustained human outpost for the first two crewed expeditions (see Figure 7). It is assumed that the crew of 4 will be on the surface for 300-400 days. A new crew would be launched every 4 years. Table 4 shows the cadence of the first 20 required launches for the first 2 crew rotations, matching the sequence diagramed in Figure 7. Launches are separated by at least 3 months, with at least 6 months wherever possible. The launches associated with SEP tug can go on virtually any date, as opposed to the ballistic transfers which are clustered around the natural opportunities.

## 5. CONCLUSIONS

In this paper, we describe a mission architecture concept for a steady-state human presence on Mars along with the cargo



**Figure 8 - Mission architecture concept using SEP tugs. a) Orbital resupply missions begin with a rendezvous of the tug and cargo in NRO, and then continue to high-Mars orbit where the cargo is left and the tug returns to NRO. b) Surface resupply missions are similar except that the tug does not go into Mars orbit and instead performs a hyperbolic flyby, drops off the landed cargo, then returns to NRO.**



**Table 4 - Representative launch sequence for the first two crewed missions to a Martian surface outpost. Nine other launches are required to position the supporting elements, two of which are for logistics. The elements that can be delivered via SEP tug have the advantage of being able to launch at almost any time. This relieves the necessity of clustering launches around ballistic opportunities.**

Launch #	Years from 1st Crew	Launch Date	Duration (yrs)	Mars Arrival	TMI	Element(s)	SEP Tug?	Destination	Separated Mass	Delivered Mass	Notes
1	-5.5	May-38	2.5	Nov-40	Tug 1	LMO-HMO Booster	Yes	HMO	30 t	25 t	RDV in NRO, Booster aerobrakes
2	-5.1	Sep-38	3.7	Jun-42	Tug 2	DSH Supply	Yes	HMO	40 t	15 t	Launch to low C3, Tug returns to NRO
3	-4.8	Jan-39	-	-	-	HAB	No	HEO	-	-	Wait for EUS for TMI (6 mos)
4	-4.3	Aug-39	1.0	Aug-40	EUS	EUS	No	HEO	-	-	TMI to Direct Entry w/ HAB
5	-4	Nov-39	0.8	Aug-40	EUS	Surface Supply	No	Surface	30 t	12 t	Direct Launch to entry
6	-2.6	Mar-41	-	-	-	Lander/MAV	No	HEO	-	-	Wait for EUS for TMI (6 mos)
7	-2.1	Oct-41	1.0	Oct-42	EUS	EUS	No	HEO	-	-	TMI to Aerocapture to HMO
8	-1.5	May-42	3.2	Jul-45	Tug 1	TEI Stage	Yes	HMO	40 t	25 t	Launch to low C3, Tug returns to NRO
1b	-1	Nov-42	-	-	-	HAB 2	No	HEO	-	-	Wait for EUS for TMI (1.3 yrs)
9	-0.5	May-43	-	-	-	MOI/DSH	No	HEO	-	-	Waits for Crew in HEO
10	0	Nov-43	0.9	Sep-44	EUS	Orion/EUS	No	HEO	-	-	Crew on ballistic to HMO
2b	0.3	Jan-44	1.0	Jan-45	EUS	EUS	No	HEO	-	-	TMI to Direct Entry w/ HAB
3b	0.8	Aug-44	2.5	Feb-47	Tug 2	LMO-HMO Booster	Yes	HMO	30 t	25 t	RDV in NRO, Booster aerobrakes
4b	1.4	Mar-45	-	-	-	Lander/MAV	No	HEO	-	-	Wait for EUS for TMI
5b	1.9	Sep-45	1.0	Sep-46	EUS	EUS	No	HEO	-	-	TMI to Aerocapture to HMO
6b	2.2	Jan-46	0.8	Oct-46	EUS	Surface Supply	No	Surface	30 t	12 t	Direct Launch to entry
7b	2.7	Jul-46	2.5	Jan-49	Tug 1	TEI Stage	Yes	HMO	30 t	25 t	RDV in NRO
8b	3.8	Aug-47	-	-	-	MOI/DSH	No	HEO	-	-	Waits for Crew in HEO
9b	4.3	Feb-48	0.8	Dec-48	-	Orion/EUS	No	HEO	-	-	Crew on ballistic to HMO
10b	4.8	Aug-48	2	Aug-50	Tug 2	DSH Supply	Yes	HMO	40 t	30 t	RDV in NRO, double resupply

Key				
Ballistic Opportunity Required	SEP Tug to HMO	Orbital Resupply	Surface Resupply	Launches associated with 2nd crew

missions needed to keep it functioning. We find that the reusable SEP tug architecture is highly beneficial to the logistics of a sustainable Mars outpost.

Fully 'Earth-Independent' human Mars missions are likely in the distant future. Several of the early Mars missions will require a robust and resilient supply chain which can instill confidence in the many stakeholders of human Mars missions. In this paper, we describe a mission architecture concept which hypothesizes such a supply chain in support of a steady-state human presence on Mars which has a resiliency that includes characteristics such as imbedded 'skip cycles'.

Given the investments being made by NASA today, such as the SLS and ARRM spacecraft bus, we find that the reusable SEP tug architecture is highly beneficial to the logistics of a sustainable Mars outpost. With the performance of SLS Block 1b and the expected performance of the ARRM spacecraft bus, both surface and Mars orbit logistic supply to Mars are enabled via an effective cadence of both ballistic transfers and low-thrust transfers. With these vehicle investments and their respective capabilities for transferring cargo to Mars, a sustainable human Mars architecture becomes not only possible, but probable within the next twenty years.

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